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MULTIPATH INDUCED TRACKING ERRORS AT 95 AND 140 GHz

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U.S. ARMY LABORATORY COMMAND

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13. ABSTRACT *(Maximum 200 words)*

The results of an experimental study to assess the effect of multipath propagation on the performance of low-angle tracking radars are described. Measurements of angular tracking errors at 95 and 140 GHz with a common conical scan antenna were made by tracking a trihedral reflector that was moved along a continuous range of heights between 0.4 and 3.6 m above the ground. Antenna diameters of 0.93 m (3 ft) and 0.62 m (2 ft) were used for propagation path lengths of 2,850.0 m and 838.4 m, respectively. The results indicate that angular error is substantially higher when tracking over snow and ice than when tracking over grass. Typically, for trihedral positions below 3.0 m, the errors induced by multipath at 95 GHz were between 0.13° to -0.20° for snow and ice and between 0.07° to -0.12° for grass. The maximum angular errors at 140 GHz under the same conditions were between 0.10° and -0.20° and between 0.04° and -0.10°, respectively.

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John N. Groff, Victor A. Leitzke, Jr., and Barry L. Reichard, also of SECAD, carefully reviewed this document and provided many thoughtful comments to the authors.

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1. INTRODUCTION

The U.S. Army is investigating millimeter wave guidance as an alternative to optical tracking and wire guidance in ground-to-ground weapons systems. The ability of a sensor to track low-angle targets on the battlefield is affected by many factors. Atmospheric turbulence, smoke and obscurants, electromagnetic interference, system noise, and multipath errors must all be considered when studying guidance system performance. The last factor, multipath, is the focus of this report.

Multipath errors are caused by returns from signals which have reflected off the earth's surface on the way to or back from the target, or both. These indirect returns interfere with the returns from signals that have traveled a direct path to the target and back to the receiver. This interference will produce a signal that may be changed in amplitude and phase from the free-space signal resulting in tracking errors. Reflection of the radar signal from a smooth, flat earth depends on the electrical properties of the ground at the point of reflection. However, the earth's surface is not smooth relative to millimeter wavelengths, so a Fresnel reflection coefficient is used to calculate the strength of the reflection. The coefficient depends on the roughness of the surface over which the signal propagates (Beckmann and Spizzichino 1963) and also upon the type of terrain cover present: grass, snow, ice, etc. The terrain profile will also have an impact on the degree to which multipath affects tracking performance. Generally, the more irregular the terrain, the more points of reflection there may be between antenna and target; whereas, a perfectly flat terrain has only one possible reflection point.

Multipath propagation can cause the target to appear higher or lower than it actually is by causing a shift in the null or by causing multiple nulls in the tracking radar antenna pattern. This condition may be exacerbated by large antenna beamwidths wherein a greater portion of the beam intercepts the ground, and more ground reflected energy will be received than for a smaller beam. Antenna beamwidths may be reduced by using a larger aperture or operating at higher frequencies. Also, the height of the antenna and target above the ground will determine the extent to which multipath will be important—the higher these are, the smaller the multipath effects will be.

Although the multipath problem has been studied for decades, there has been relatively little investigation of this phenomenon in the millimeter wave range of the electromagnetic spectrum. One of the early millimeter wave studies (Kammerer and Richer 1964) was conducted by the U.S. Army Ballistic Research Laboratory (BRL), Aberdeen Proving Ground, MD. The data, taken at 68 GHz, showed that

angular pointing errors of less than one-tenth of the beamwidth could be achieved with null-type conical scan pointing techniques. Another BRL investigation (Wallace 1979) compared measured data to specular reflection multipath theory to derive forward scattering coefficients at 140 GHz for various types of ground cover. It was concluded that ground with vegetative cover has a coefficient less than or equal to -0.1; for asphalt, it is about -0.5. This points out that millimeter-wave multipath problems may be less serious when propagating over vegetated surfaces than over surfaces such as asphalt because the power of the undesired, reflected signals will be reduced by absorption and the reflected signals diffused by a relatively rough surface.

To improve our understanding in this area, an experiment was designed to measure at 95 and 140 GHz simultaneously the effects of multipath interference on the tracking accuracy of a conical scan radar. The experiment was conducted during the winter of 1986–1987 at Redstone Arsenal, AL, and at Aberdeen Proving Ground, MD.

2. DESCRIPTION OF RADAR AND INSTRUMENTATION

The radar instrumentation used to make the measurements, including radar-controlling software, was designed and fabricated by the BRL. The instrumentation consisted of a dual frequency radar, a vertical probe, and a data acquisition facility.

The radar system used to make measurements of angular pointing errors consisted of two pulsed radars operating simultaneously at 95 and 140 GHz through a common aperture. Diplexing of the two radars was accomplished by using an orthomode transducer and a scalar-feed horn to illuminate a Cassegrain antenna. The polarizations of the radars were thus orthogonal and were rotated so they were both at a 45° angle to the ground. The orthomode transducer and horn were W-band units which produced approximately 3 dB more two-way loss at 140 GHz than at 95 GHz.

The two radars employed impact avalanche transit time (IMPATT) oscillators, which were pulsed alternately to avoid interference. A voltage-controlled automatic gain control (AGC) circuit was employed with video "box car" integrators to maintain a large dynamic range. The AGC signal was sampled by a Masscomp 533 data acquisition computer to measure amplitude variations. The angular errors were derived by synchronously detecting the AGC voltage with a four-quadrant timing signal taken from the conical scan control circuit. Azimuth and elevation gain and phase were controlled separately to obtain

the minimum cross talk between recorded angular error signals. During the course of a measurement, the AGC, azimuth, elevation, and target height positions were continuously digitized by the data acquisition computer at a higher rate than the target vertical position was updated. Figures 1 and 2 show samples of AGC measurements versus position measurements.

Figures 3 through 6 show the two-way horizontal and vertical antenna patterns at 95 and 140 GHz of the 0.62-m antenna used at Aberdeen Proving Ground (APG). The patterns were measured with a calibrated trihedral reflector placed 550 m from the antenna to ensure far-field conditions were met using the approximation (Balanis 1982):

$$R_f \geq \frac{2D^2}{\lambda}, \tag{1}$$

where the diameter of the antenna dish (D) is 0.62 m, the wavelength (λ) at 140 GHz is 2.14 mm, and the far-field (R_f) is 503 m. The 95-GHz far-field would be closer (longer wavelength λ), so the 550-m range is valid for both frequencies.

The azimuthal pattern was measured by positioning the antenna subreflector so that the beam was at each of its maximum azimuthal positions. An azimuthal scan of the radar mount provided a record of signal level versus mount angle (Figures 3 and 5). The patterns in Figures 4 and 6 were measures of the elevational pattern made in the same manner.

A visual inspection of the patterns reveals that for both frequencies, the beamwidth for the azimuthal sweep is larger than the beamwidth for the elevational plane sweep. As expected, the 6-dB two-way beamwidth of the antenna at 95 GHz is slightly larger than the corresponding beamwidth at 140 GHz. At 95 GHz, the 6-dB beamwidth is 0.35° in the azimuthal and 0.33° in the elevational direction. At 140 GHz, the beamwidth is 0.32° for the azimuthal and 0.30° for the elevational direction.

Antennas with narrow beams have more sensitivity to deviations of the target from the beam axis and experience less error in the presence of multipath. The angular sensitivity of a particular beam pattern is derived from the shapes of the two offset beams shown in Figures 3 through 6. Taking the difference of the two offset beam patterns gives the normalized error signal versus angle, commonly called an "S-curve," and makes the measured angular error independent of signal amplitude (Barton and Ward

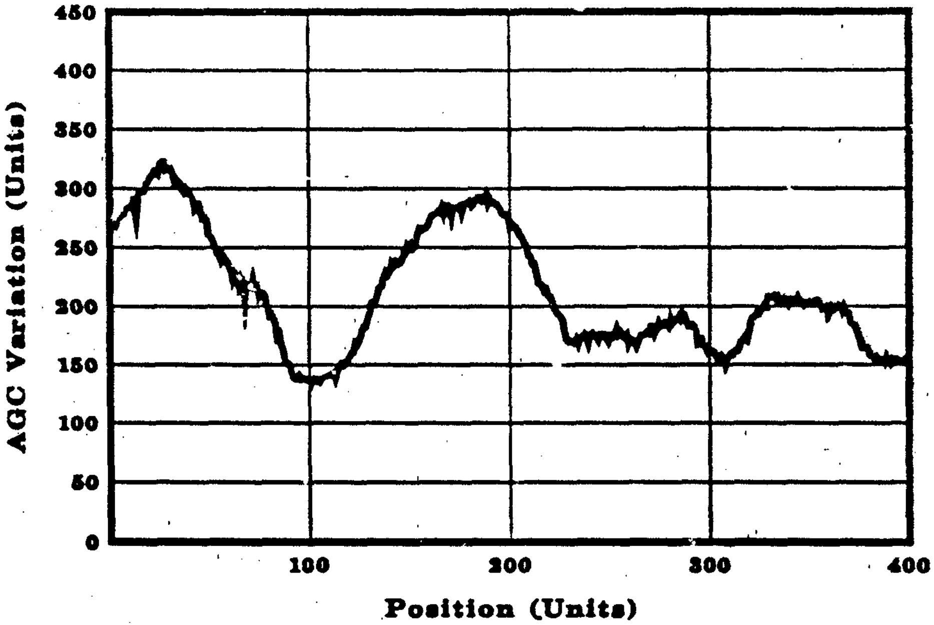

Figure 1. Typical Amplitude Data at 95 GHz.

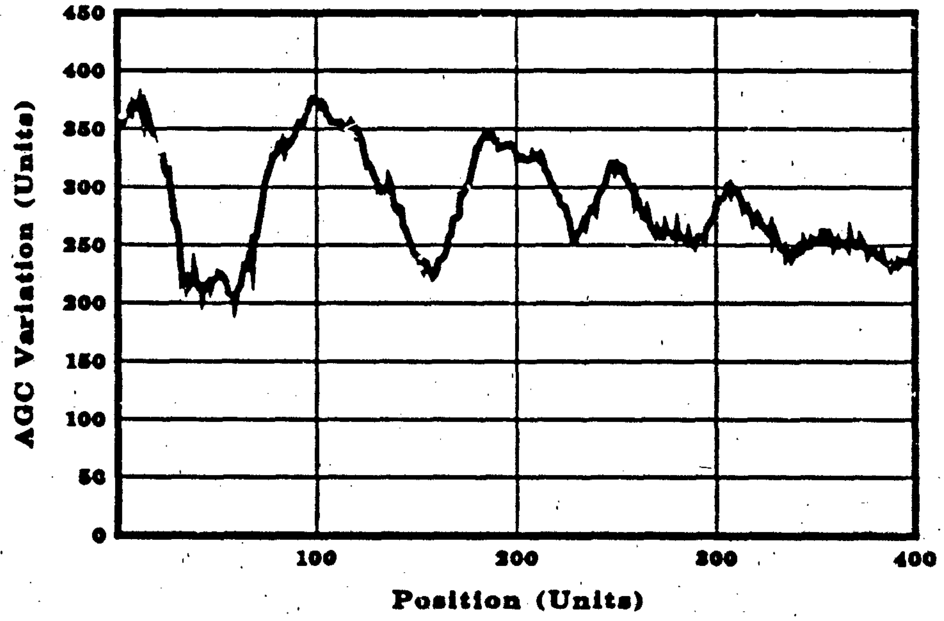

Figure 2. Typical Amplitude Data at 140 GHz.

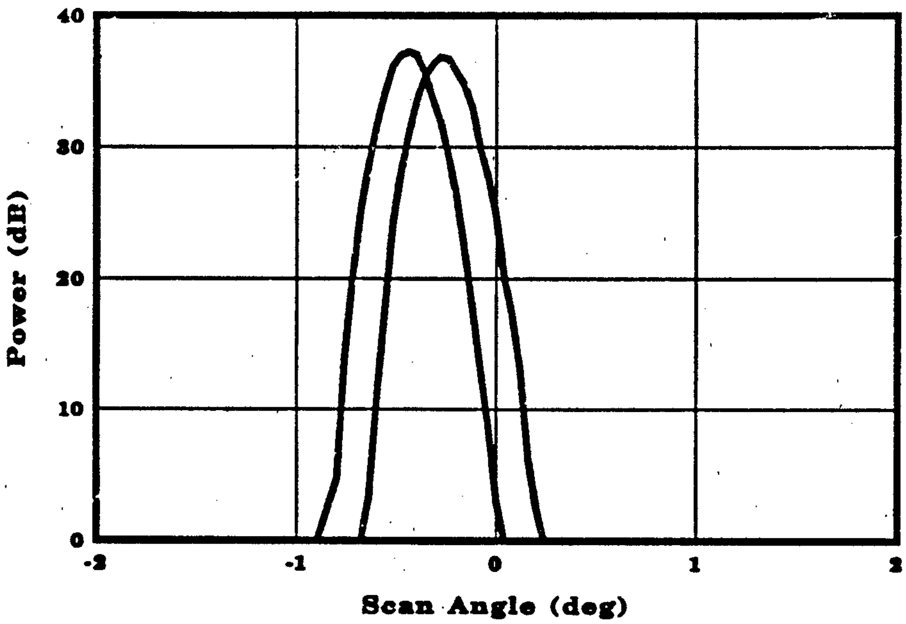

Figure 3. 95-GHz Two-Way Antenna Pattern, Azimuth.

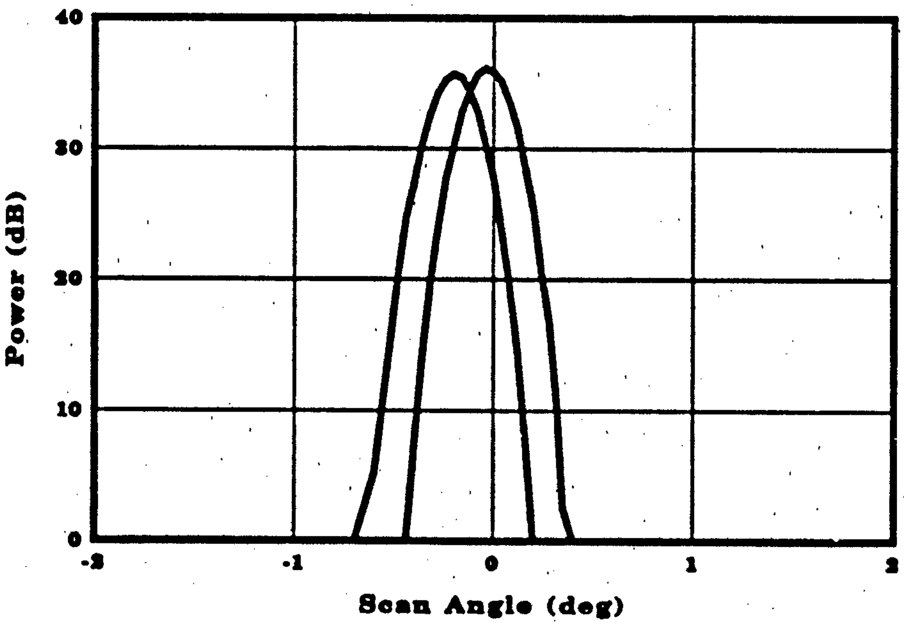

Figure 4. 95-GHz Two-Way Antenna Pattern, Elevation.

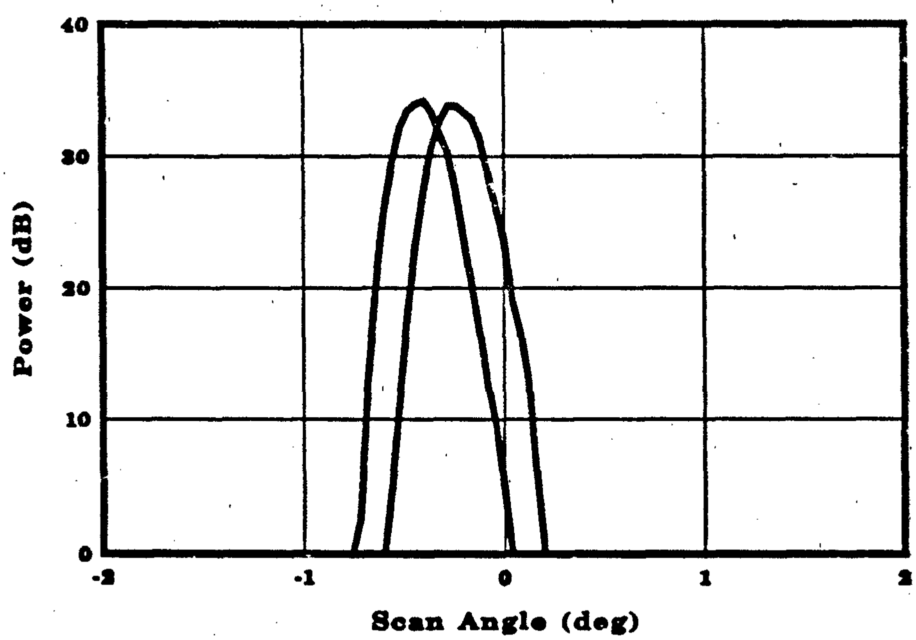

Figure 5. 140-GHz Two-Way Antenna Pattern, Azimuth.

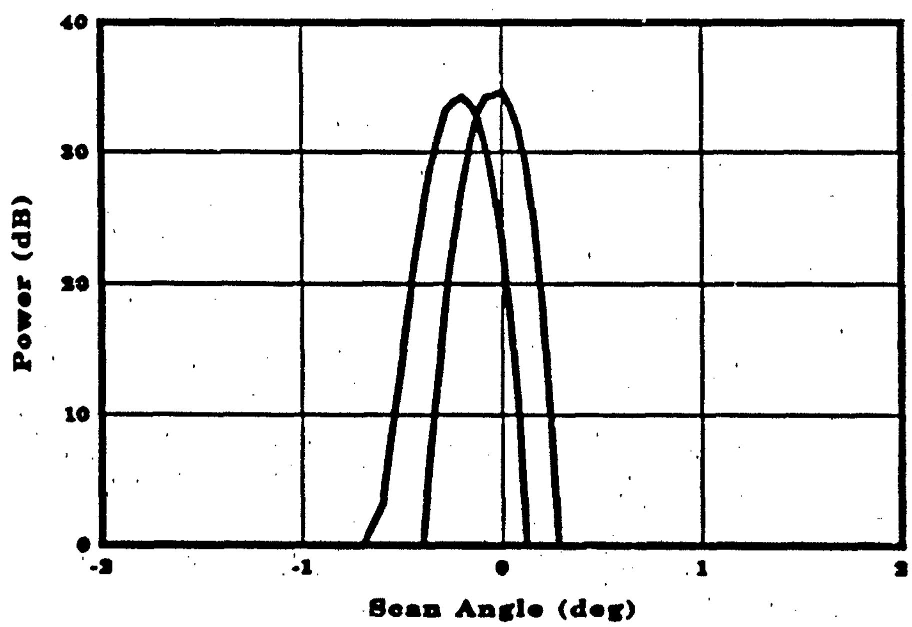

Figure 6. 140-GHz Two-Way Antenna Pattern, Elevation.

1984). Near the center of the S-curve, the beam pattern difference is a linear measure of the off-axis angular error. Figures 7 and 8 show measured S-curves for the 95 and 140 GHz radars, respectively.

While the 0.62-m antenna proved adequate for the APG trials, the much longer propagation distance at Redstone required a narrower beamwidth to maintain tracking accuracy. A 0.93-m antenna with it's correspondingly lower beamwidth was used for all of the Redstone test.

The vertical probe consisted of a mounting for a trihedral corner reflector driven by a threaded rod on a 3.6-m pole. The threaded rod was turned by a motor that could automatically translate a reflector up and down the pole at a constant speed. The position of the reflector was monitored by a digitally controlled pulse generator whose period of oscillation was varied linearly with position by counting the rotations of the threaded rod. This pulse train was then transmitted down the range over a twisted pair of wires to the instrumentation van. The center of travel along the probe pole was 2.0 m above the ground. The vertical probe employed in the experiment is shown in Figure 9.

The radar system was placed on a Scientific Atlanta 4116A positioner control/mount system and could be moved remotely in azimuth or elevation by a control in the BRL instrumentation van. Figure 10 shows the shelter for the instrumentation radar and the 2-1/2-ton truck in which the signal processing equipment and computer were housed. In setting up the radar for tracking the moving target, the antenna was boresighted on the probe reflector, which was positioned at the center of travel on the vertical probe. The antenna was aimed at the center for the duration of each trial. The movement of the probe reflector was observed from inside the radar van by means of a television monitor, which had been optically boresighted to within ±0.003° of the center of the radar beam.

As the trihedral moved, vertical and horizontal error voltage signals from the 95- and 140-GHz radars, the probe height, and the time of measurement were recorded continuously with the Masscomp 533 data acquisition system. When a trial was completed, error signals versus target position could be viewed on a "quick-look" uncalibrated basis using the Masscomp on-line graphics software.

3. EXPERIMENTAL PROCEDURE

3.1 <u>Site Description and Test Conditions</u>. Two different test sites were used during the course of the experiment in an attempt to observe the effect of different terrain profiles and surfaces on tracking accuracy.

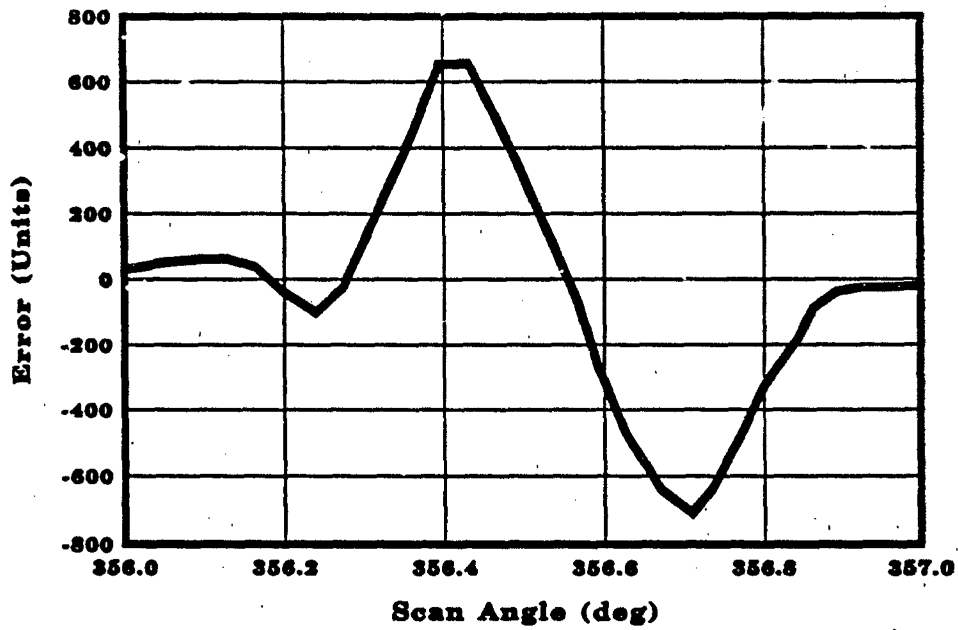

Figure 7. Measured Elevational S-curve at 95 GHz.

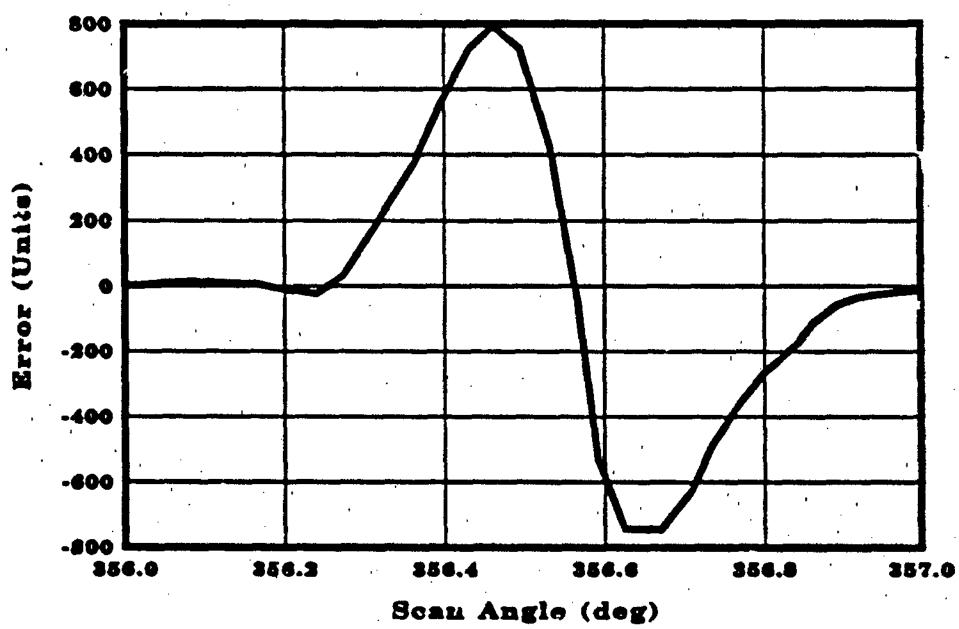

Figure 8. Measured Elevational S-Curve at 140 GHz.

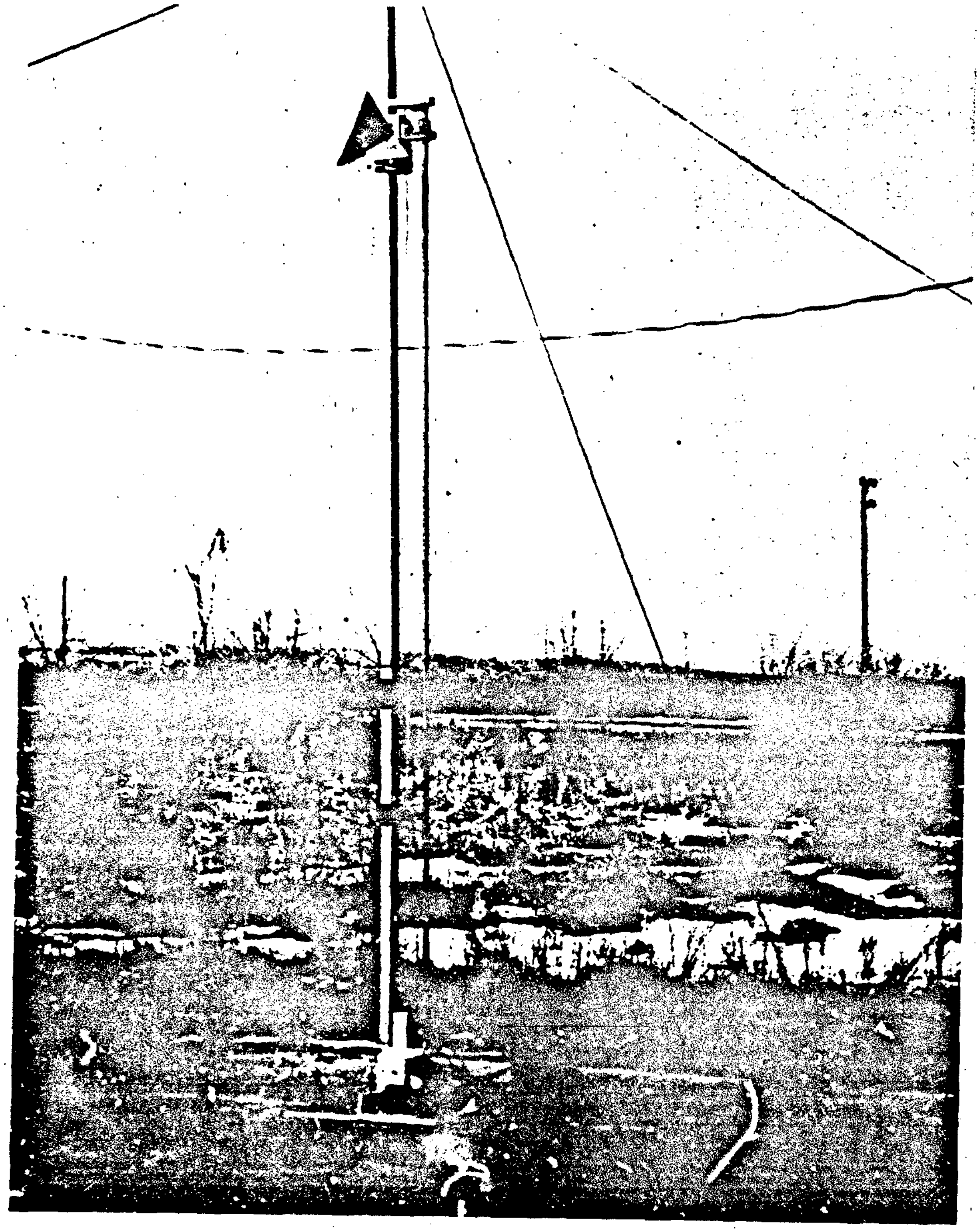

Figure 9. Vertical Probe at Maximum Height.

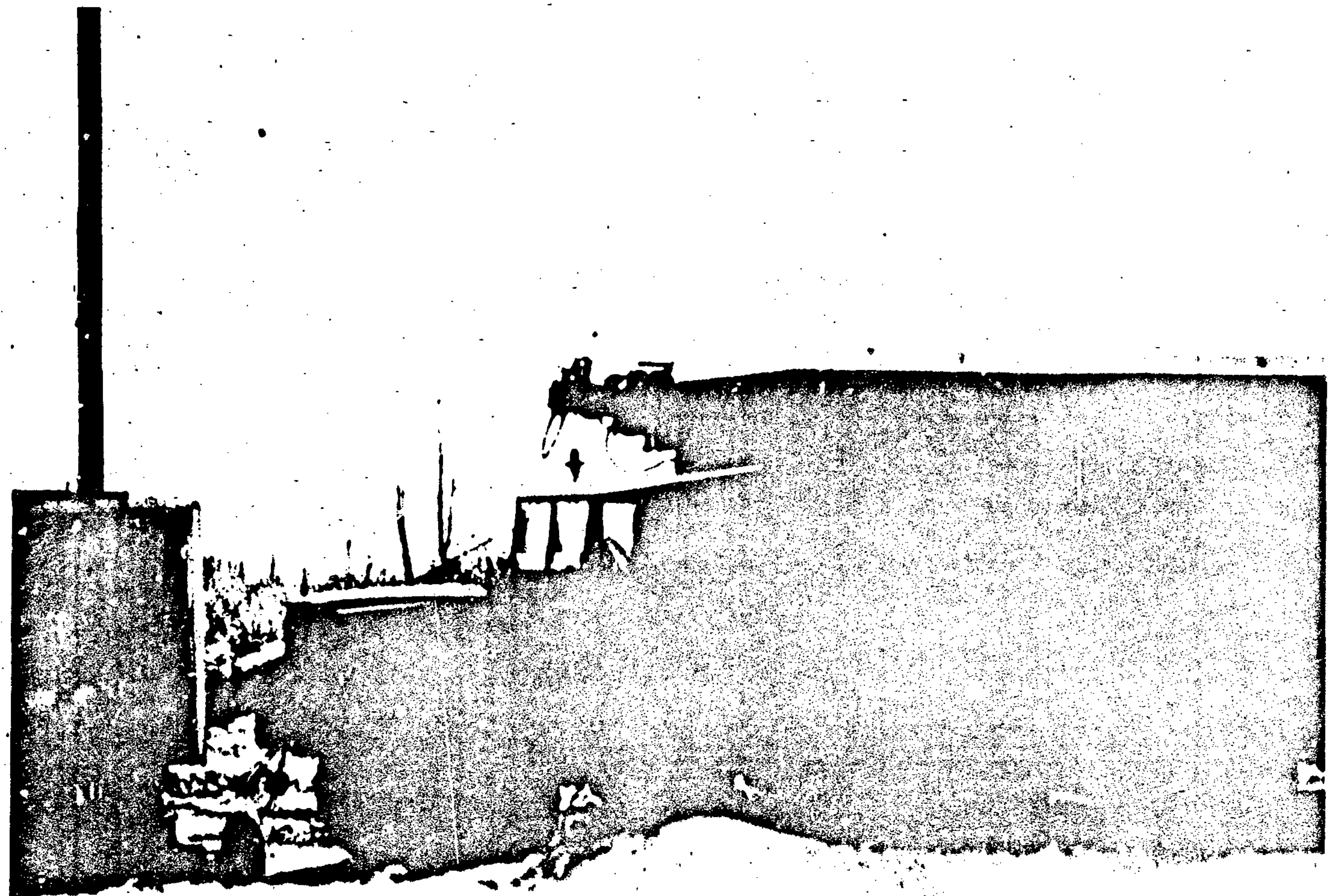

Figure 10. Conical Scan Antenna and Instrumentation Van.

The first site was the Redstone Arsenal Test Area 3; it was a slightly rolling cow pasture that had been plowed and was covered with long, dead grass. The terrain profile for the test site is shown in Figure 11. The profile was measured using seven reflectors placed along the 2,850-m antenna/target path with pole heights adjusted so that each reflector aligned with the optical line of sight to the vertical probe. The heights of the poles were then measured, and the terrain profile was easily deduced from the resulting measurements.

The second site was the Aberdeen Proving Ground (APG), electromagnetic propagation (EMP) range; it contained no vegetation other than dead grass and weeds in the vicinity of the propagation path. The terrain profile for the Aberdeen test is not shown because it is essentially flat and varies no more than six inches in height over its 838.4-m length. This can be seen in Figure 12, where the test range is shown with a light covering of icy snow.

Data was recorded on 5 December 1986 at Redstone Arsenal, and on 30 January 1987; 5, 17, 19, 20, 23, and 24 February 1987; and 26 March 1987 at APG. Measurements were made over the APG terrain with a variety of ground cover conditions: grassy, snowy, and icy. The decision to record data on any particular day was based on the weather and ground conditions. A synopsis of the logbook that was kept throughout the course of the experiment is included in the Appendix. Descriptions of the conditions that existed on any days during which measurements were taken can be found there.

3.2 Test Procedures. The experimental setup is shown in Figure 13. The radar antenna was positioned at 1.5 m above the ground at Redstone and 1.1 m above the ground at APG, and the beam axis of its conical scan was pointed at the center of travel of the trihedral corner reflector mounted on the vertical positioner.

The trials run each day included one with the probe running from top to bottom of the positioner, and one with it running from bottom to top, to verify that the measurements were repeatable. Another corner reflector, whose cross section was known very accurately, was positioned on a stationary pole near the probe but out of the measurement path, to act as a boresight reference. The signal level measured off the reference reflector was used to periodically check the calibration of the radars and to make sure the signal levels and error signals were not drifting during the course of a day's trials. Measurements were restricted to days with calm to moderate winds to avoid sway of the probe.

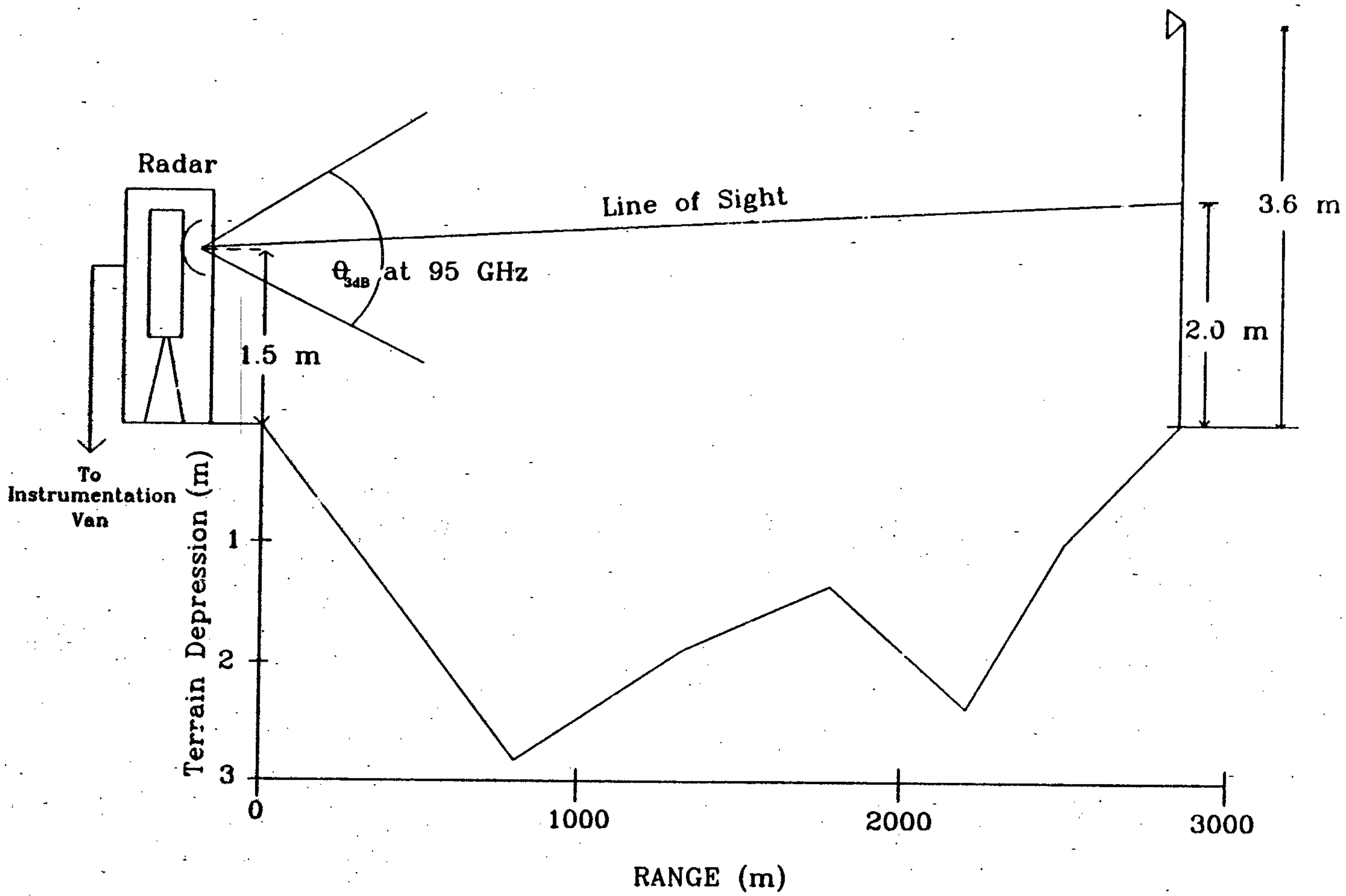

Figure 11. Terrain Profile for the Redstone Arsenal Test Area 3.

Figure 12. Multipath Test Range at APG.

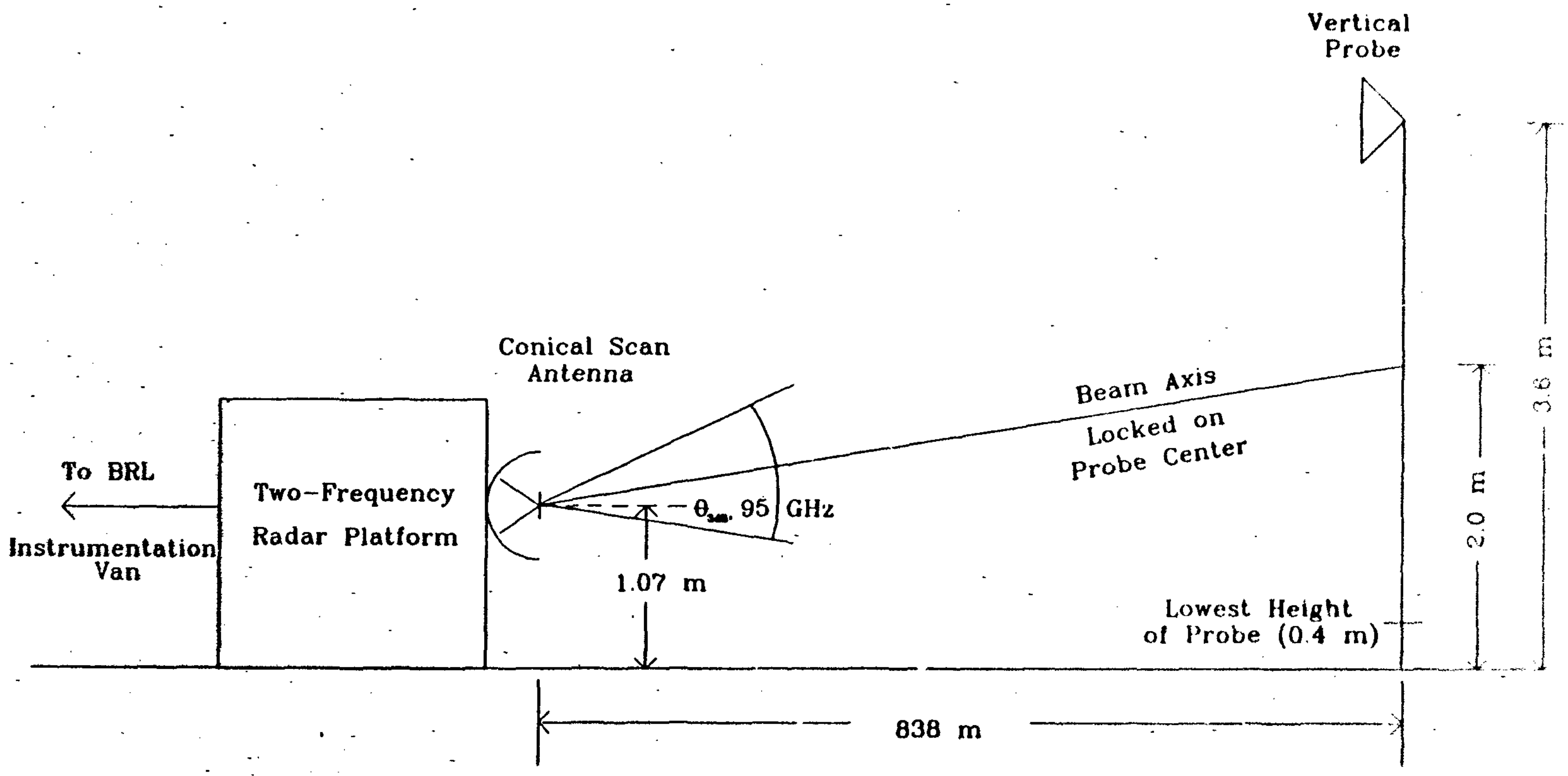

Figure 13. Basic Geometry of the Experiment at APG.

An S-curve was measured before each trial run, and each curve was used in calibrating the set of error voltage measurements which followed. To measure an S-curve, the antenna mount was swept vertically over the target reflector. The reflector was placed on a pole tall enough to ensure the antenna beam did not strike the ground. Examples of such vertical S-curves are shown in Figures 7 and 8. Azimuthal S-curves were similarly measured by sweeping the antenna from left to right across the target reflector.

4. ANALYSIS OF MULTIPATH PROPAGATION DATA

4.1 Calibration of Data. Figures 1 and 2 show typical AGC signals versus probe position before calibration and filtering. Processing the raw data was a three-step process that consisted of: 1) converting angular error voltages from "unit" error in Analog-to-Digital bits (12-bit integer representations of the actual voltage values) to angular error in degrees, 2) converting the position axis from "unit" position to meters above ground and, 3) filtering the data with a smoothing algorithm.

The angular error voltage was calibrated to give angular error by using information derived from the S-curves recorded before each trial. The straight-line section in the middle of each S-curve was used to compute a slope. The slope is in units of units/degrees, as can be seen in Figures 7 and 8. The digitized angular error voltage values were scaled by this slope value resulting in angular error in degrees.

Next, the position axis of the raw data was calibrated. The pulse generated output from the vertical probe contained position information in terms of uncalibrated "units." This value would change every time the probe moved an inch along its path. Thus, the number of inches the probe moved during a trial could be determined by counting the number of position value changes. This count was then converted from inches to meters to give the total distance moved during the trial in meters. Finally, the total distance in meters was added to the measured minimum height above ground of the probe to give the position information as "distance above ground."

In some instances, two consecutive samples of angular error voltage had the same probe position value (in "units"), indicating that the probe had moved less than an inch between signal measurements. In these cases, the two samples for this probe height were averaged, and the averaged value was then associated with this probe height in subsequent calculations.

The last step in reducing the data was smoothing to get rid of the noise that may have otherwise obscured the more interesting multipath effects. The noise was caused by the lateral movement of the probe pole as the corner reflector was being raised or lowered and by the wind causing the weeds at the reflection point to ripple. The curves were smoothed using a 10-point moving average. The resulting calibrated angular error versus target height curves are shown in Figures 14 to 28.

4.2 Observations. Table 1 presents a summary of the data presented in Figures 14 through 28. The peak-to-peak angular errors are shown for the different conditions over the course of testing. Some of the more interesting features are not easily compiled into a table. When different trials on the same day yielded the same value for peak-to-peak angular error, that value is listed in the table for that day.

In the plots shown in Figures 1 and 2, the target height is increasing as the unit position increases. These plots demonstrate how the spatial frequency of oscillation of the multipath induced errors decrease with decreasing elevation angle according to the equation (Barton and Ward 1984):

$$F_m = \frac{2hE}{\lambda}, \qquad (2)$$

where F_m is the frequency of cyclic multipath error, h is the height of the antenna (which is constant in this case), λ is the wavelength (also constant), and E is the rate of target elevation angle change as seen by the radar. From the geometry, it can be seen that if E stays constant, then equal changes in target height will lead to faster cycling at the upper positions.

Inspection of the data leads to several observations. The errors at Redstone consistently stayed below the null, whereas the Aberdeen data showed the error oscillating around the null, albeit sometimes making large excursions from it. This bias below the nominal boresight is attributed to a mechanical shift of the boresight when the radar aim point was moved from the calibration target to the vertical probe. This setup problem did not exist at APG.

Another difference observed between the data from the two sites is that when both sites are covered with dead grass, the maximum peak-to-peak error of the angular error curve oscillations is larger for the Aberdeen data than the Redstone data, for both frequencies. At Redstone, a peak-to-peak angular error of 0.05° for 95 GHz was measured; at Aberdeen, it was 0.11°. At 140 GHz, the difference becomes even more apparent with a 0.01° angular error at Redstone and a 0.08° error at Aberdeen.

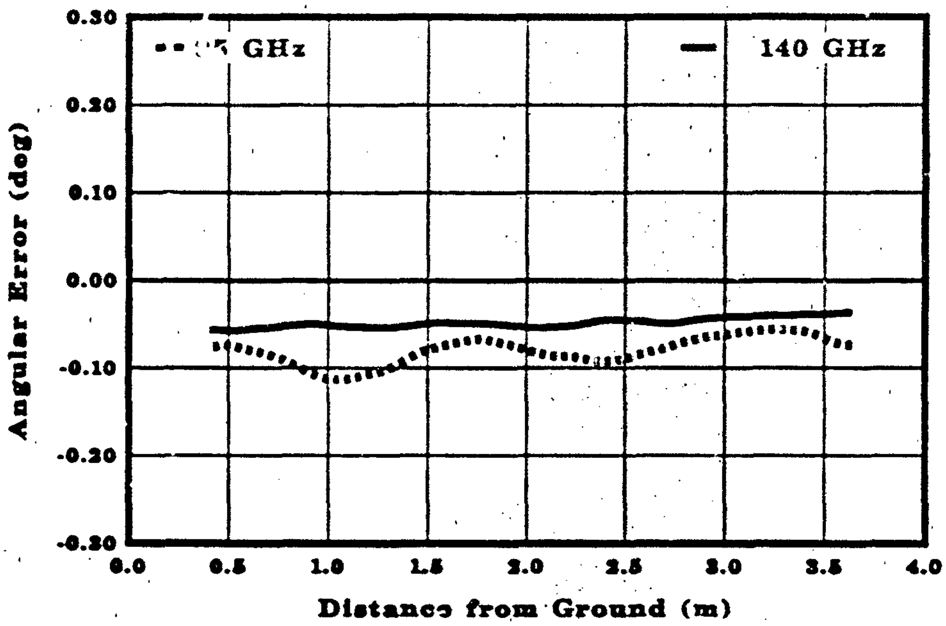

Figure 14. Calibrated Angular Error for December 5th, Trial 1 at Redstone Arsenal.

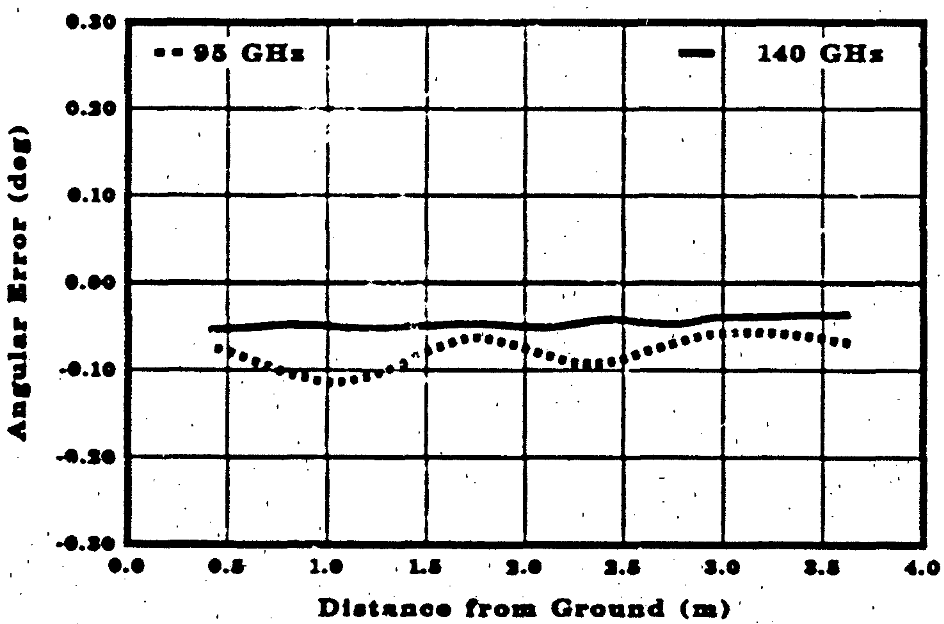

Figure 15. Calibrated Angular Error for December 5th, Trial 2 at Redstone Arsenal.

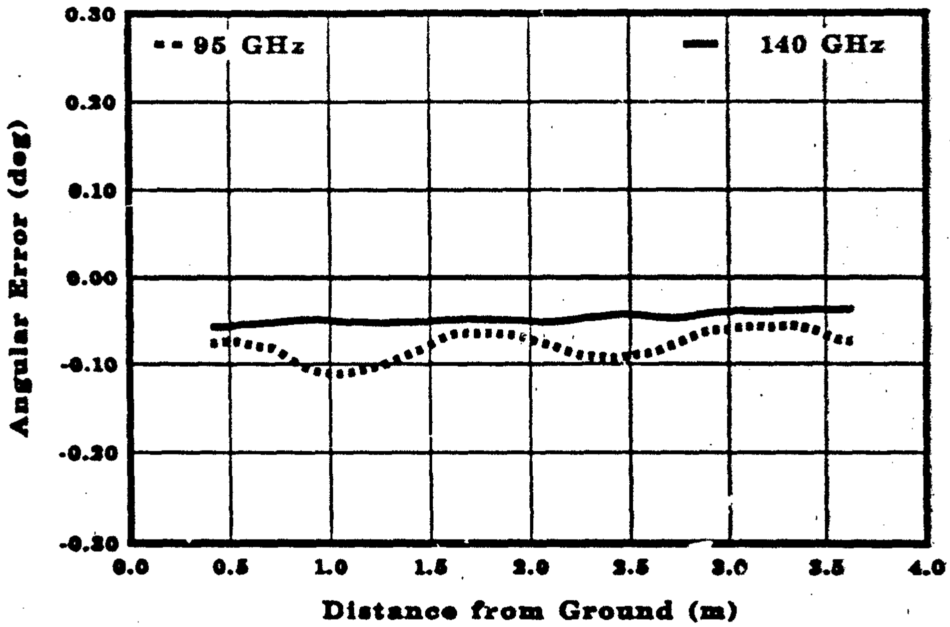

Figure 16. Calibrated Angular Error for December 5th, Trial 3 at Redstone Arsenal.

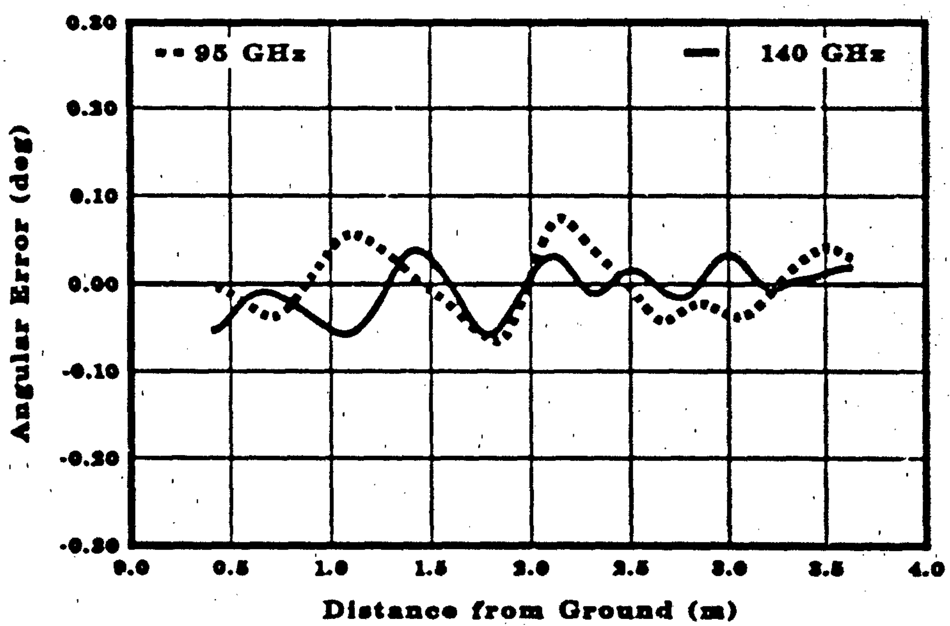

Figure 17. Calibrated Angular Error for February 5th, Trial 1 at APG.

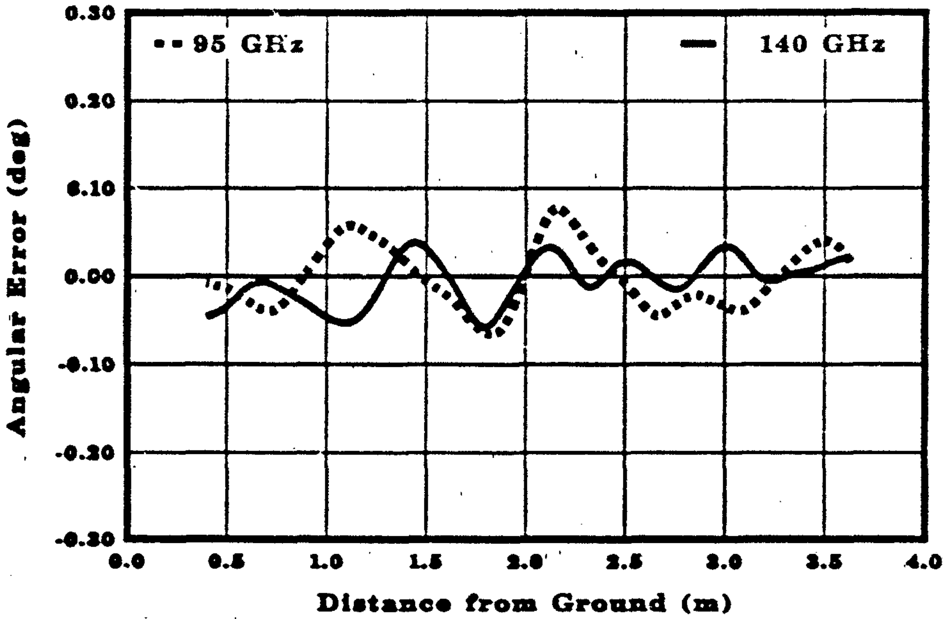

Figure 18. Calibrated Angular Error for February 5th, Trial 2 at APG.

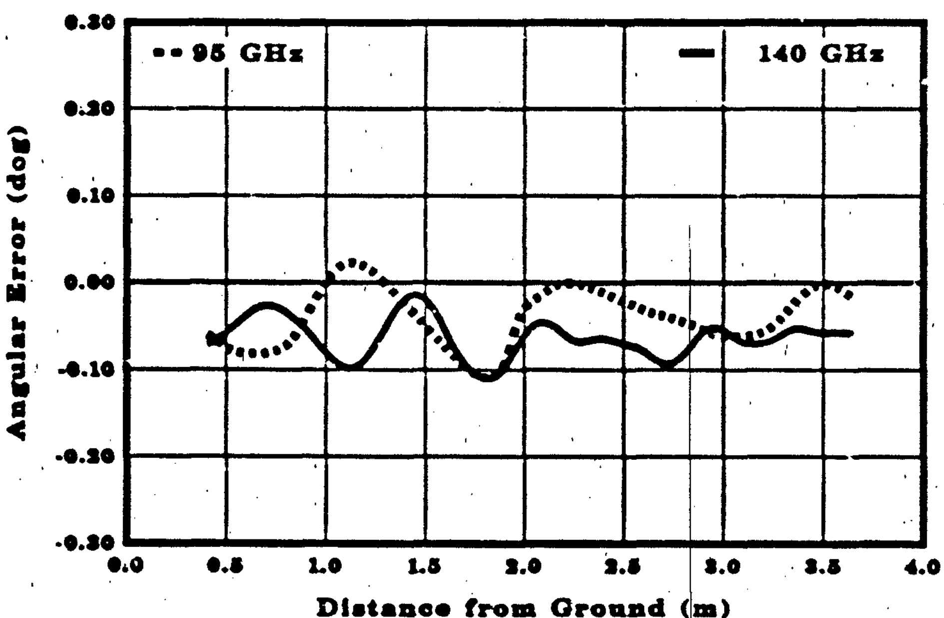

Figure 19. Calibrated Angular Error for February 17th at APG.

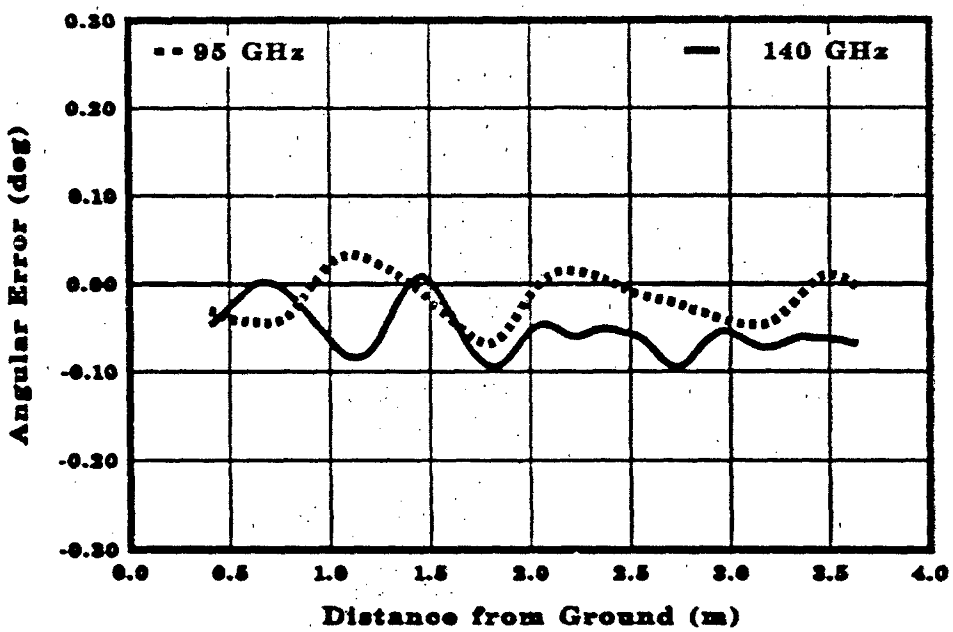

Figure 20. Calibrated Angular Error for February 19th at APG.

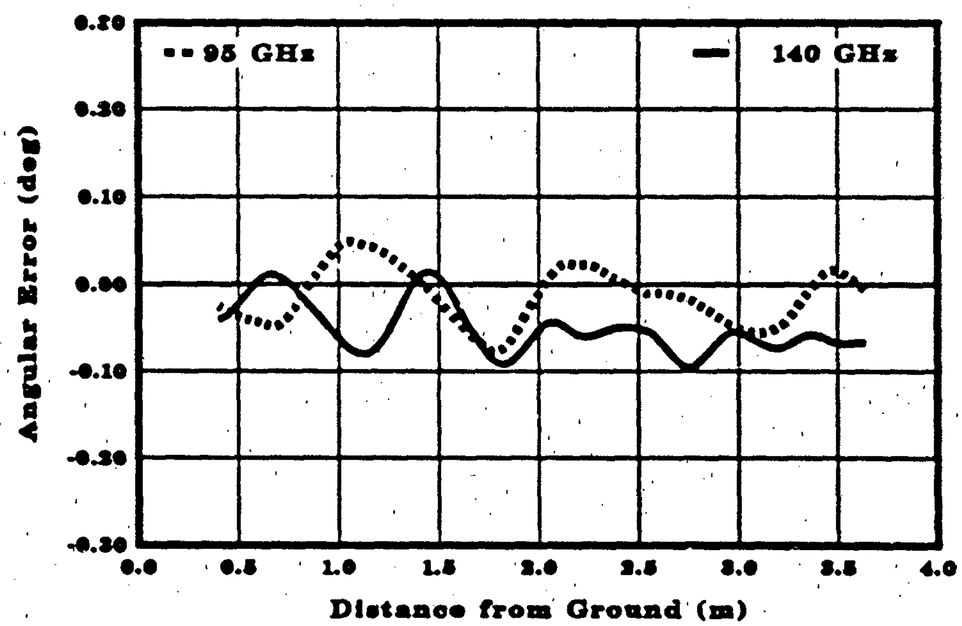

Figure 21. Calibrated Angular Error for February 20th, Trial 1 at APG.

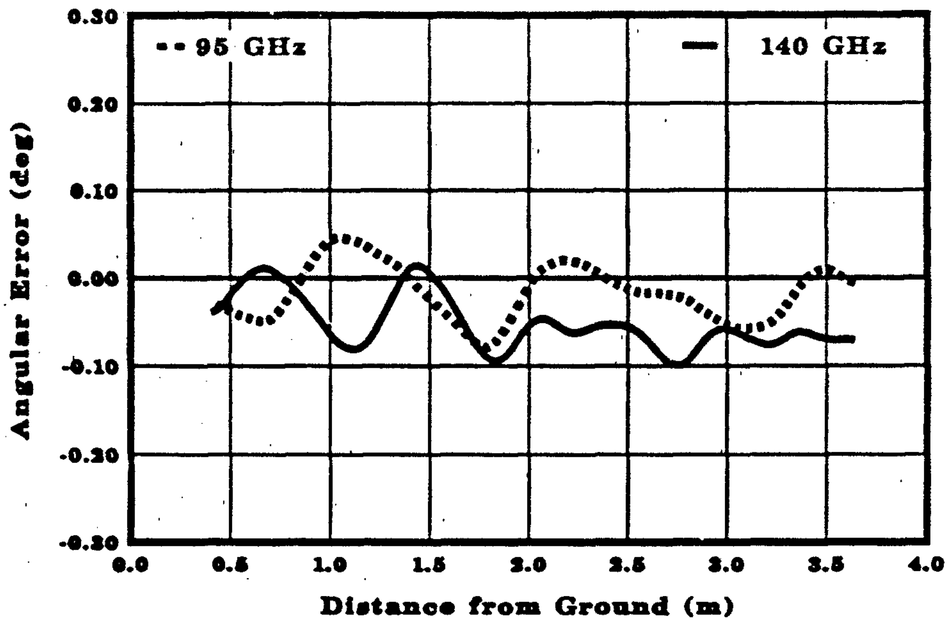

Figure 22. Calibrated Angular Error for February 20th, Trial 2 at APG.

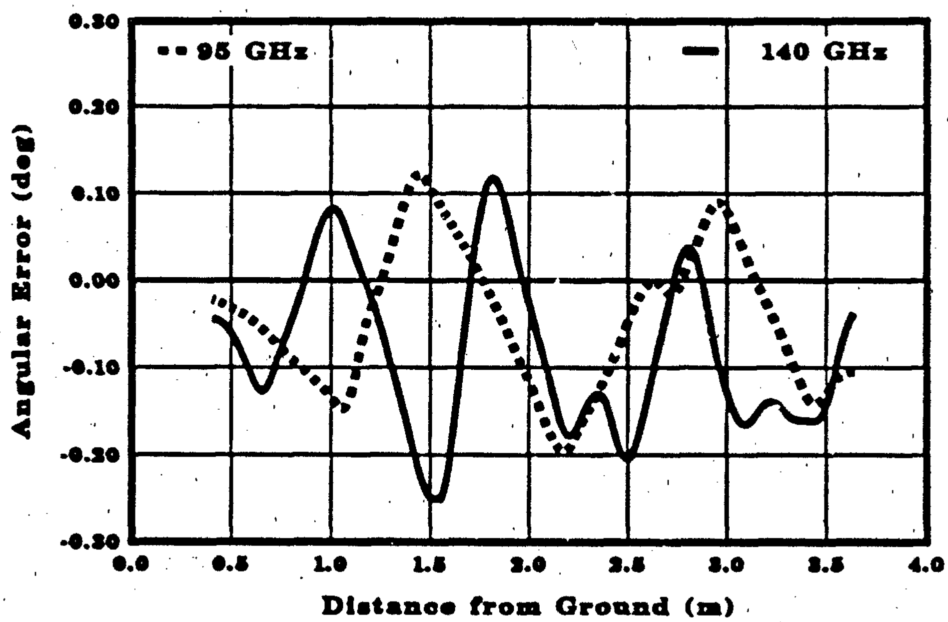

Figure 23. Calibrated Angular Error for February 23rd, Trial 1 at APG.

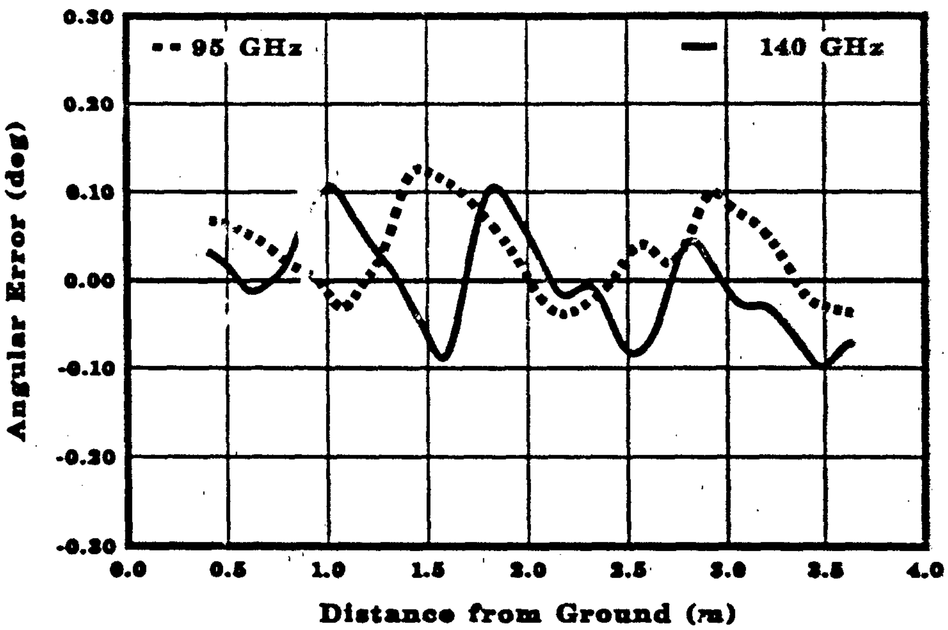

Figure 24. Calibrated Angular Error for February 23th, Trial 2 at APG.

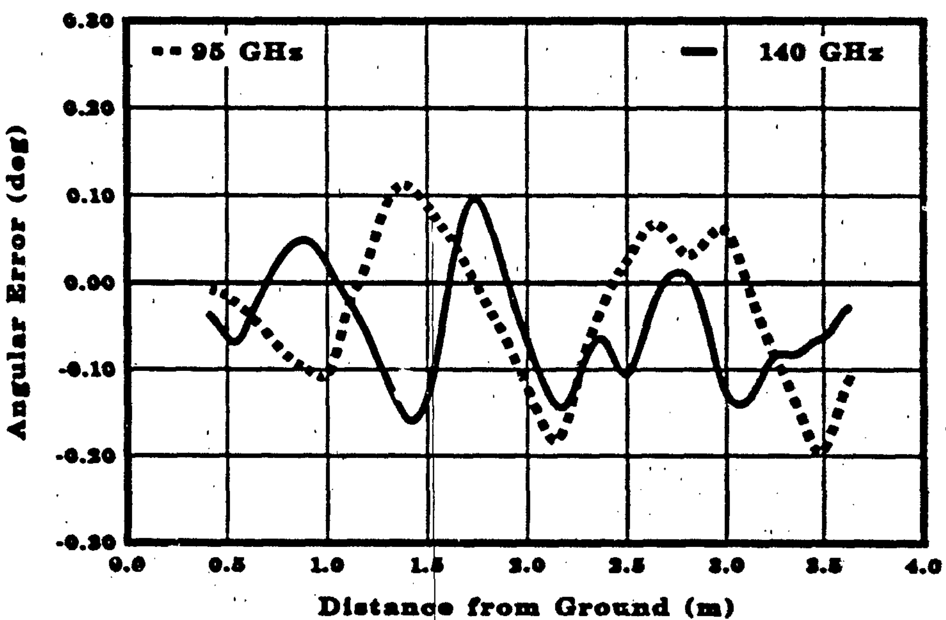

Figure 25. Calibrated Angular Error for February 24th, Trial 1 at APG.

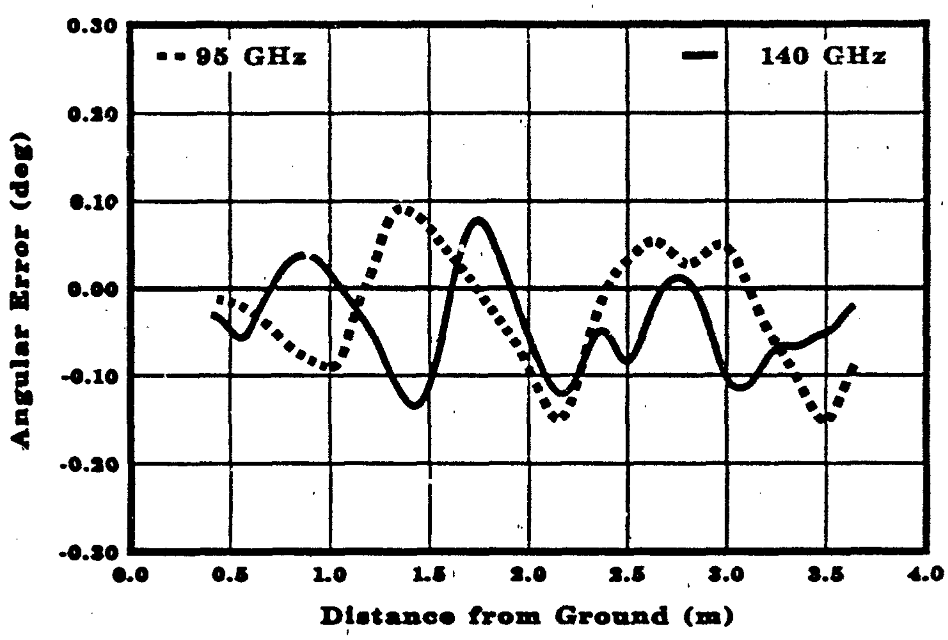

Figure 26. Calibrated Angular Error for February 24th, Trial 2 at APG.

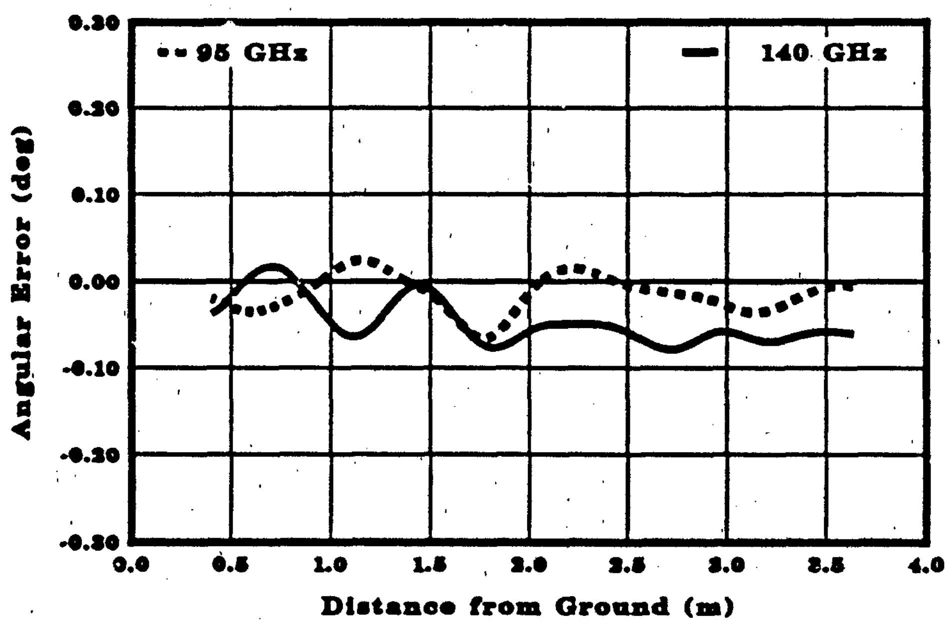

Figure 27. Calibrated Angular Error for March 26th, Trial 1 at APG.

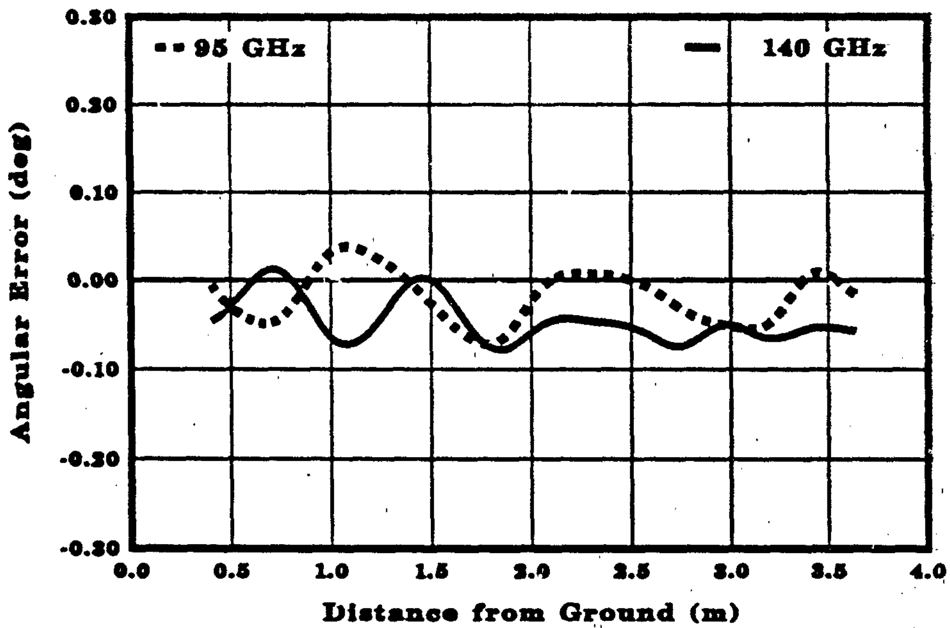

Figure 28. Calibrated Angular Error for March 26th, Trial 2 at APG.

The Aberdeen data taken between 20 February and 26 March show the effect of going from a relatively snow-free terrain (mostly grass showing with patches of snow) to one covered with 35 cm of snow and then back to a dry terrain. The maximum angular error for the 95-GHz radar, 0.2°, occurred on the day it snowed. Before the snow, it was 0.07°, and after the snow had cleared, it dropped back down to 0.07°. The largest variations in angle error also came on the day it snowed; however, they were still large on the following day after an overnight freeze turned the ground cover into a crusty ice. The melting water on the snow day and the ice that formed the following day increased the surface reflection coefficient, thereby increasing the ground reflected beam strength and adding to multipath interference. The 140-GHz data followed the same general pattern during these changing ground conditions. The maximum angular error at 140 GHz was -0.25°, but a return to grassy conditions caused the error to drop back down to levels recorded before the snowfall.

Just as with the AGC signal, the spatial frequency of the angular error cycling increases as the probe reflector height increases. Measurements on the data sets indicate that the ratio of the oscillations of the 95-GHz to the 140-GHz curves is within ±15% of the ratio of the two wavelengths over all the data sets.

Table 1. Peak-to-Peak Errors for Various Conditions

Date	Freq., GHz	Terrain Profile	Ground Cover	Angular Error Peak-to-Peak, deg
5 Dec	95	RA	Grass	0.05
	140			0.01
5 Feb	95	APG	Crusty	0.14
	140			0.10
17 Feb	95	APG	Patchy	0.13
	140			0.10
19 Feb	95	APG	Melt	0.10
	140			0.10
20 Feb	95	APG	Melt	0.13
	140			0.11
23 Feb				
TR 1	95	APG	Snow	0.32
TR 1	140			0.37
TR 2	95	APG	Snow	0.16
TR 2	140			0.20
24 Feb				
TR 1	95	APG	Crusty	0.29
TR 1	140			0.25
TR 2	95	APG	Crusty	0.24
TR 2	140			0.21
26 Mar	95	APG	Grass	0.11
	140			0.08

Notes: APG = Aberdeen Proving Ground.
Crusty = snow crusted over with ice.
Melt = melting snow.
RA = Redstone Arsenal.
Patchy = patches of snow and ice.

It can easily be seen from the geometry of specular reflection that this should be a constant equal to 95/140. Also, as the target climbed above the terrain, the magnitude of the angular errors got smaller; however, on days with snow and ice cover, the error is still significant at the maximum target height.

5. CONCLUSIONS

1) The peak-to-peak angular error is greater for the lower-frequency, wider-beamwidth radar in all but two cases, both of them being under melting snow and high surface moisture conditions.

2) In general, the angular error over grassy terrain was greater at Aberdeen than at Redstone. The difference was particularly noticeable at 140 GHz. To a great extent, this was due to the very different terrain profiles of these test sites.

3) The angular error on days when the ground is grassy is smaller than on days when the ground is covered with snow or ice.

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APPENDIX:

EXPERIMENT LOGBOOK ENTRIES

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DATA LOG

Redstone

5 December 86

Range was 2850 m. Antenna height above ground was 1.5 m. Probe height varied from 0.4 to 3.6 m. Frequencies used were 95 GHz and 140 GHz, which were transmitted cross polarized, 45° off the vertical. The optical boresight was fixed at the center of the probe. Terrain was plowed and covered with long grass and had some bare, muddy areas. The range was fairly level over the first half of its course, and then it started to fall off over the second half (as we moved towards the probe).

Trial 1 began at 1455 hours, with probe running from top to bottom of pole.

Trial 2 began at 1511 hours, with probe running from bottom to top of pole.

Trial 3 began at 1525 hours, with probe running from top to bottom of pole.

Aberdeen

Measurements took place at the electromagnetic propagation (EMP) range. Ground roughness was similar to that on the Redstone range. However, the EMP range is fairly level, changing no more in elevation than six inches over its entire distance of 838 m.

30 January 87

No log entry.

Trial began at 1456 hours, with probe running from bottom to top of pole.

The 140 data appears to be greatly different than the other 140 curves. This data will not be used in the analysis.

5 February 87

Snow over entire field, frozen last night.

Trial 1 began at 0837 hours, with probe running from top to bottom of pole.

Trial 2 began at 0848 hours, with probe running from bottom to top of pole.

17 February 87

Frozen ground, with small patches of frozen snow and some ice in low areas.

Trial began at 1445 hours, with probe running from top to bottom of pole.

19 February 87

Some partly frozen ground, small patches of melting snow, and water in low areas.

Trial began at 1455 hours, with probe running from top to bottom of pole.

20 February 87

No log entry.

Trial 1 began at 1438 hours, with probe running from bottom to top of pole.

Trial 2 began at 1459 hours, with probe running from top to bottom of pole.

23 February 87	Overnight snow, approximately 14 inches. Warm day with very wet snow approximately 11 inches deep.
	Trial 1 began at 1314 hours, with probe running from bottom to top of pole.
	Trial 2 began at 1341 hours, with probe running from top to bottom of pole.
24 February 87	Snow approximately 11 inches deep. Very hard freeze overnight, thick crust.
	Trial 1 began at 0826 hours, with probe running from bottom to top of pole.
	Trial 2 began at 0841 hours, with probe running from top to bottom of pole.
26 March 87	No entry in log of ground conditions. Assumed dry.
	Trial 1 began at 1416 hours, with probe running from bottom to top of pole.
	Trial 2 began at 1428 hours, with probe running from top to bottom of pole.

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